

**The role of attention control in mediating the relationship between Hick reaction time
slopes and intelligence**


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Abstract

In 1993, psychologists found that the Hick Task, a commonly used task to explore the relationship between speed of information processing (SOIP) and reaction times, may have results due to attentional breadth confounds (Bors et al., 1993). However, there were no studies that attempted to replicate this finding. In our study, we aimed to replicate the results of Bors et al. (1993) and expanded it by including attention measures. We recruited 44 participants from the Georgia Tech and Atlanta communities and asked them to complete cognitive tasks. We retained the attentional breadth confound in our “spread” condition but eliminated it with our “center” condition. We hypothesized that participants would have faster reaction times on the center condition, that reaction times in the center condition would correlate more strongly with attention and intelligence measures, and that attention measures would correlate to intelligence measures. A repeated-measures ANOVA found that there was a significant difference between reaction times on the 1-bit spread and 1-bit center conditions, but no such relationship between the 0-bit and 1-bit spread conditions. Additionally, the only significant correlation was between the two 1-bit reaction times. These findings were not what we expected, but give insight into future directions, including repeating the study with a more diverse sample, and exploring why there is an unexpected relationship between the 1-bit center and spread conditions.

Keywords: Attention control, Intelligence, Reaction times, Speed of information processing

Introduction

Hick's Law states that reaction times (RTs) on a task increase linearly with the logarithm of possible response options. This is traditionally done using log base 2, which allows for stimulus uncertainty to be expressed as bits, or binary digits, of information (Proctor & Schneider, 2018). Studies based on Hick's Law show a correlation between RT on simple cognitive tasks and intelligence—the RT/IQ correlation (Bates & Stough, 1997; Larson & Saccuzzo, 1989). RTs on the Hick task are negatively correlated with intelligence, so that high intelligence is associated with smaller (and thus faster) RTs. There has been much debate over how to explain this correlation.

There are at least two approaches to understanding the correlation between intelligence and RT. The speed of information processing (SOIP) theory assumes that more intelligent people have faster nervous systems, which cause them to react quickly on tasks (Bors et al., 1993). The other approach assumes that it is not the mere SOIP in the brain that regulates a faster RT, but instead more effective attention control. Higher attention control capabilities may allow people to monitor the larger portions of their visual field at once, making them more sensitive to changes taking place within a given area and leading to reduced RTs on visual tasks (Bates & Stough, 1997). This research aimed to answer whether individual differences in Hick RTs are related to differences in attention control.

One study is especially important to this research question. The work of Bors et al. (1993) controlled for an attentional breadth confound in a commonly employed Hick paradigm, which eliminated the correlation between Hick RTs (RT) and Raven's Advanced Progressive Matrices (RAPM) performance, a widely used measure of intelligence (Bors et al., 1993). This suggests that attributing the Hick RT/IQ correlation to SOIP differences may be an error, and

that the crucial factor underlying the relationship between Hick RT and intelligence is the ability to deploy attention across larger surface areas (Bors et al., 1993). However, these findings have not been replicated or further explored.

Our research project had participants complete the Antisaccade task, RAPM, and Hick Task. Our Hick Task contained a condition that retained the attentional breadth confound, as well as one where the confound was controlled for. Afterward, we calculated Pearson correlations for the RAPM, Antisaccade, and Hick tasks. Additionally, we used a repeated-measures analysis of variance (ANOVA) to investigate the effect of bit condition on Hick Task RTs. We expected to find a significant effect of bit condition on Hick RTs, as well as significant correlations between Hick task RTs and performance on the RAPM and Antisaccade.

Literature Review

In 1952, the theory of modern communication was becoming popular, which aimed to describe the transmission of a signal through a communication channel. The quality of a transmission could be judged by the amount of information, in binary digits, or bits, that was transmitted. Hick (1952) aimed to bring the concept into psychology, where the possibility of mathematically quantifying information and uncertainty showed potential for advancing scientific inquiry about cognition. After replicating an experiment done in 1885 by Merkel, Hick (1952) found that RTs on a task increased linearly with task complexity (Proctor & Schneider, 2018). Hyman (1953) replicated and expanded upon Hick's initial findings. Therefore, this relationship is referred to as Hick's Law, or the Hick-Hyman Law (Hick, 1952; Hyman, 1953; Proctor & Schneider, 2018). The relationship between task complexity and RT as explained by Hick's Law is important because it revealed a powerful relationship between a mental process and observed behavior.

Jensen (1987) incorporated findings from the Hick task into his own theory of intelligence, where SOIP underlies intelligence. This approach assumes that the brain works like a computer, where faster SOIP reflects faster "hardware" working in the brain. Jensen set up a version of Hick's paradigm to test his theory and found that there was a correlation between RT and intelligence (the RT/IQ correlation), as a function of the slope between increasing stimuli complexity and RTs on a task (Longstreth, 1984). Since then, many studies have been interested in what causes the RT/IQ correlation.

However, there are flaws in Jensen's methodology, most notably confounds between bit values and attentional breadth (Longstreth, 1984). Jensen used and popularized an experimental device where response options with lights under them are arranged in a semi-circle around a

home button. A participant starts with their finger on the home button, and after a light is turned on, they must move their finger to press the corresponding response option. Longstreth (1984) points out the semi-circular set up of these response options introduces a confound between attentional breadth and bit conditions in the stimulus array, such that some individuals may not be capable of apprehending the entire display at once. When Bors et al. (1993) tested Jensen's findings, they controlled for attentional breadth by replacing the semi-circle design of the Jensen apparatus with one box that the participants had to attend to. After doing this, they found that the RT/IQ correlation broke down (Bors et al., 1993). This brought into question whether Jensen's interpretation of the RT/IQ correlation is valid. This is important because the conclusions of Bors et al. (1993) imply that experiments using Jensen's paradigm may have results that are caused by a confound (i.e., individual differences in attentional breadth) instead of the factor being studied (i.e., individual differences in SOIP).

The idea that Jensen posed, however, that SOIP underlies intelligence, was already picking up steam. Researchers using SOIP to explain the RT/IQ correlation could support their claim with the fact that using RTs as performance on easy cognitive tasks shows a moderate, significant negative correlation with intelligence on the Sternberg, Hick, and Posner tasks (Neubauer et al., 1997). This would mean that as a person's intelligence increases, their RT on the tasks given to them would decrease, due to a faster SOIP. It has since been established that there is substantial shared variance between SOIP and intelligence, although the magnitude of this estimate varies considerably (Conway et al., 2002; Frischkorn et al., 2018).

Importantly, some studies suggest that it is the speed of *specific* mental processes that are important to intelligence, as compared to general processing speed (Schubert et al., 2017). In a study of these specific benefits, researchers found that more intelligent people are faster in

updating information, selecting a response from a set of given choices, and evaluating sensory information when compared to others (Schubert & Frischkorn, 2020), at least some of which has been argued to depend on attention control (Heitz & Engle, 2007; Shipstead et al., 2016).

One hypothesis that researchers pose for explaining the correlation between RT and intelligence is that SOIP is one of many functions that overlap and have a multiplicative effect on intelligence (Schubert et al., 2018). An important part of this hypothesis is the Worst Performance Rule, which might reflect limitations in specific cognitive processes, such as attention control (Schubert et al., 2018). The Worst Performance Rule states that a person's worst RT on a task is most indicative of their intelligence, where many excessively slow trials are associated with lower intelligence (Coyle, 2003; Schubert et al., 2018). Variability in RTs across complex tasks support the idea that intelligence is made up of multiple parts, a key assumption in our research design. These components include attention control and working memory, a system that temporarily maintains information while allowing for that information to be manipulated (Larson & Saccuzzo, 1989).

In our view, individual differences in working memory capacity are largely driven by individual differences in attention control, and measures of working memory capacity reflect information maintenance in the face of distractions (Bleckley et al., 2014). Additionally, in a study that used an fMRI scan to record participants while completing the Hick task, researchers documented increased activity in regions of the cognitive control network, including areas that are associated with attention (Wu et al., 2018). Therefore, it is important to consider the role of attention control in the RT/IQ correlation, potentially as a mediator in the relationship. The key premise of this approach is that more intelligent participants control and allocate attentional

resources in a goal-directed manner more effectively than their less intelligent counterparts, leading to faster responses.

A notable weakness of studies using SOIP to explain the RT/IQ correlation is that experimentally manipulating SOIP is difficult. This is important to the research topic because successful manipulation of a variable is one of the key concepts for showing causation—therefore an approach must be taken that comes close to it. In one of the few studies that manages to manipulate SOIP (by means of a nicotine patch), results reflect temporary benefits in reducing RTs on tasks, but with no increase in intelligence test scores (Schubert et al., 2018). In another experiment, both SOIP and working memory load were manipulated (Kofler et al., 2019). Slowing SOIP did not have a significant effect on working memory performance, whereas changing working memory did significantly slow SOIP (Kofler et al., 2019). This suggests that working memory abilities (which are intertwined with attention control abilities) are involved in efficiently processing information and could help explain the RT/IQ correlation.

However, as promising as these connections may seem for an attention control explanation, there is a critique to be mentioned as well: the definition of attention is one that varies across the literature. In the literature, controlled attention has been defined as all of the following: performance on one of three executive function domains, a component of working memory, a concept that is effectively the same as working memory, or a concept independent of working memory (Schubert & Rey-Mermet, 2019). Thus, it is important to note what the definition of attention is in any of the studies that are discussed to pinpoint what its connection with intelligence is hypothesized to be. For the purposes of this study, attention is defined as a process related to (but distinct from) working memory that helps determine what enters, exits, and occupies working memory.

Researchers have linked individual differences in intelligence to several attention-related phenomena, including sustained attention, spatial attention, and the breadth of attention. Some studies have found that the RT/IQ correlation is mediated by lapses in attention, where more lapses in attention slow the average RT of an individual, which is correlated with lower intelligence (Coyle, 2017). This finding also helps explain the Worst Performance Rule, where an individual's slowest RT would be reflective of how many lapses in their attention are occurring (Coyle, 2017). Finally, other researchers have posed that the correlation between performance on the Hick task and intelligence strengthens under divided attention conditions (Roberts et al., 1988). This can also be supported with another study of interest, which found that working memory capacity was correlated with the breadth, or effective distribution over a large area, of attention (Krietz et al., 2015). If this correlation were true, larger working memory capacities (due to its relationship with attention control) would be associated with shorter RTs in a Hick task when the attentional breadth confound is retained. Incidentally, this account coincides precisely with the results of Bors et al. (1993).

Although the reviewed evidence is open to interpretation, we favour the use of attention control to explain the RT/IQ correlation over using SOIP. Therefore, we incorporated measures of attention control into our research design to test this hypothesis. It is also difficult to establish directionality of effects. One tool that can help establish plausible directionalities is a repeated-measures ANOVA, which allows us to assess the effect of experimental manipulations (spread/center condition and 0/1-bit condition) on RTs. Using an ANOVA is justified given the design of this experiment, since we had a continuous dependent variable (RT), and a categorical independent variable that had three levels (0-bit, 1-bit spread, and 1-bit center conditions).

In summary, the studies discussed earlier provide an avenue through which further research can be conducted on the relationship between attention control and the RT/IQ correlation. Attention control is related to working memory, and working memory is related to the breadth of attention (Bleckley et al., 2014; Krietz et al., 2015). The findings of Bors et al. (1993) show that the RT/IQ correlation is eliminated when attentional breadth demands are reduced. This suggests that the RT/IQ correlation observed in the Hick task could be due to breadth of attention. Since breadth of attention is related to working memory and attention control, it is possible that attention control is responsible for the RT/IQ correlation. We pose that increased intelligence is reflective of higher attentional breadth capacities, which in turn are related to RTs. By this account, faster RTs should correlate negatively with intelligence and with attention control, but only when the attentional breadth confound is retained in our Hick Task. Further, we expect to there to be a significant difference between RTs based on Hick Task condition, with larger RTs in the 1-bit spread condition than in the 1-bit enter or 0-bit conditions.

Method

Participants

Our study included 44 participants ($M_{age} = 20.7$, $SD_{age} = 3.18$) from the community in and around Atlanta and Georgia Tech. Subjects were recruited voluntarily and were given \$55 in compensation for their participation in the study. Additionally, Georgia Tech students were able to choose whether they wanted monetary compensation or class credit. Subjects were recruited primarily from the r/gatech subreddit and Georgia Tech's SONA system. All participants were required to be in between the ages of 18 and 35, either native English speakers or those who learned English before the age of 5, have normal or corrected-to-normal vision, live in the United States, and not have had a seizure before.

Materials

Participants completing their sessions for the experiment were in one of three rooms in the Attention & Working Memory Lab for the study. These rooms were equipped with a monitor attached to both a Windows 10 and Windows 7 CPU, headphones, an eye tracker, and a station six feet away for an undergraduate research assistant to run the experiment. A demographics questionnaire and consent form was developed by the graduate students in the lab and approved by the Georgia Tech IRB. The full experiment consisted of roughly 15 tasks distributed across two data collection occasions, with only some tasks being relevant to this study. All tasks used in this experiment were created using E-Prime version 3.0.

Raven's Advanced Progressive Matrices Task

Participants were shown abstract shapes in a 3 x 3 matrix. One of the shapes was missing, and participants had to indicate, via mouse click, which of the presented options best fit the overall pattern in the matrix. Subjects had 10 minutes to complete 18 trials.

Antisaccade Task

Participants focused on a fixation point for 2000-3000 ms, followed by a warning noise being played for 300 ms. An asterisk appeared on either the left or right side of the screen, followed by the letter “O” or “Q” being displayed for 100 ms on the opposite side of the screen. Then, the letter was masked, and participants indicated on their keyboard which letter they saw. There were a total of 72 trials, and participants had 10 minutes for this task.

Modified Hick Task

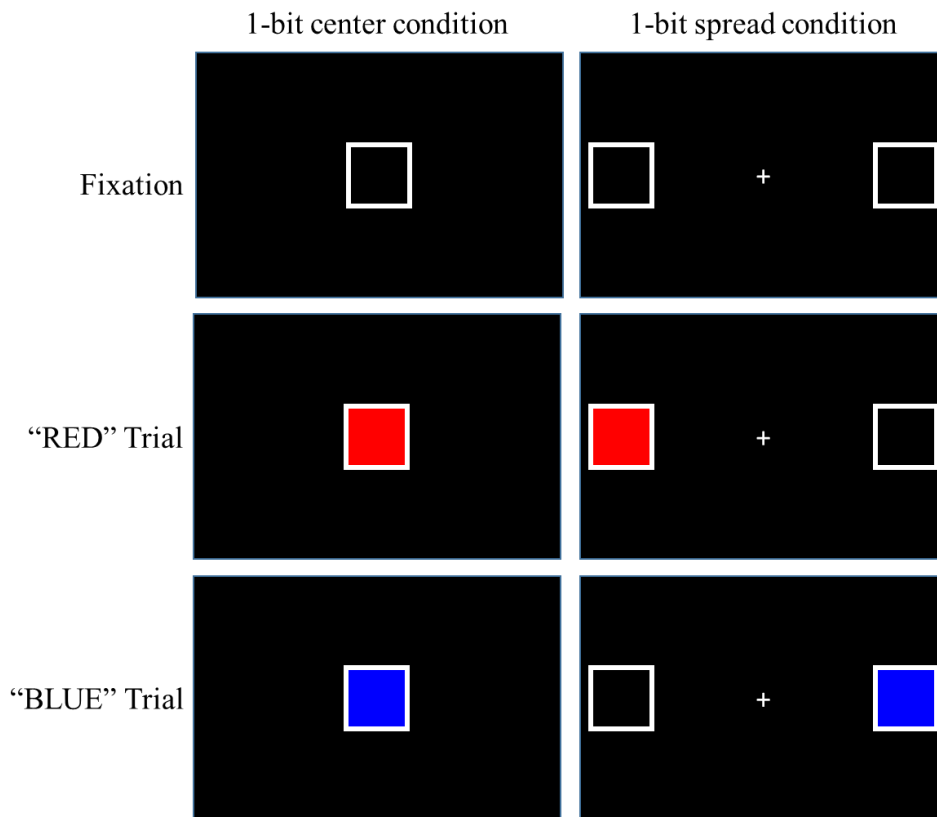
Our version of the Hick Task (see Figure 1) consisted of three trial types organized into four blocks. Participants first completed one block of 24 0-bit trials. On these trials, participants were informed in advance of what the incoming response would be (Blue or Red). The response was always the same within the first and last half of 0-bit trials, and whether blue trials or red trials occurred first was randomized. Then, participants completed a block of 24 trials of either the 1-bit spread or 1-bit centered condition, in which they had to decide whether a color appearing on the screen was red or blue, with both responses occurring randomly and with equal frequency. Afterward, participants completed another block of 0-bit trials, followed by the other block of 1-bit condition trials. The order of the 1-bit conditions was randomized across participants.

On each trial, participants stared at a fixation screen on the center of the screen. In the 0-bit and 1-bit center conditions, this consisted of an empty square in the center of the screen. In the 1-bit spread condition, this consisted of a fixation cross with empty squares to the left and right. After a delay of 2000-3000 ms, a colour would fill the box (or one of the boxes in the 1-bit spread condition), and participants would have to indicate what colour had filled the box. Responses were given by pressing a button on a response box. Response options in the 0-bit

condition were always the same within-block (either always red or always blue), while response options in the 1-bit conditions varied by trial (with either red or blue on every trial). Participants completed a total of 96 trials, with there being twice as many 0-bit conditions as 1-bit center and 1-bit spread. It took participants approximately 12 minutes to finish this task.

Figure 1.

Modified Hick Task Conditions.



Note. Examples of the 1-bit center conditions (left) and 1-bit spread condition (right). 0-bit trials were identical to the 1-bit center condition, except the correct response did not vary from trial to trial.

Design

Our study had a within-subjects design. Three dependent variables were calculated and then correlated with each other. First, mean RTs on the Hick task were computed separately for

the 0-bit, 1-bit spread, and 1-bit center conditions using only correct trials. Data from the two 0-bit blocks were averaged to form a single summary statistic. Second, an attention control score was calculated using proportion of correct responses on the Antisaccade task. Finally, intelligence scores were calculated using the dependent variable of scores (number correct out of 18 trials) on the Raven's APM task.

Procedure

Participants in the study first completed an informed consent form and demographics questionnaire. Afterward, they completed roughly two hours to computerized testing. A second data collection session was completed in the same way, omitting informed consent and the demographics questionnaire. Upon completion of each session, participants were mailed a check (\$25 for session 1, \$30 for session 2). Participants who did not complete all sessions, or who engaged in abnormal activities during their sessions (falling asleep while doing tasks, checking their phones often, not listening to instructions, etc.) were removed from final analyses and, if applicable, were not invited to return to finish the study.

Results

All data processing and analysis was completing using jamovi (The jamovi project, 2019). All descriptive statistics for the Hick, Antisaccade, and RAPM tasks are reported in Table 1. Data appeared normally distributed with acceptable skewness and kurtosis values.

Table 1

Descriptive Statistics of All Measures

Variable	n	Mean	SD	min	max	Skewness	Kurtosis
0bit	44	324	75.7	202	535	0.91	0.44
Center_1bit	44	359.22	44.99	273.04	492.71	0.77	0.94
Spread_1bit	44	331.48	51.01	257.32	472.29	0.54	0.11
Antisaccade	39	0.78	0.15	0.36	0.99	-0.69	0.03
RAPM	44	10.80	3.46	1	16	-0.76	0.20

Note. RAPM = Raven's Advanced Progressive Matrices. 0-bit, 1-bit-center, and 1-bit-spread refer to conditions of the Hick Task.

Table 2 shows correlations between all measures used in the study. There was a significant correlation between performance on the Hick Task 1-bit-spread and 1-bit-center conditions ($r = 0.614$, $p < 0.001$). No other significant correlations were found between measures, and all were numerically small in value (less than $|\cdot 30|$).

Table 2

Pearson Correlation Matrix Between All Measures

	0 bit	Spread/1 bit	Center/1 bit	RAPM	Antisaccade
0 bit	---	0.260	0.295	-0.255	0.022
Spread/1 bit		---	0.614***	-0.204	-0.130
Center/1 bit			---	-0.246	-0.176
RAPM				---	-0.036
Antisaccade					---

Note. RAPM = Raven's Advanced Progressive Matrices. *** = $p < 0.001$.

A one-way repeated-measures ANOVA was conducted to analyze the effect of Hick Task Condition on RTs. A Greenhouse-Geisser degrees of freedom correction was applied to account for violating the sphericity assumption. Using Type 3 sum of squares, the initial ANOVA revealed that there was a significant effect of Hick condition on RTs ($F = 6.53$, $df = 1.45$, $p < 0.001$). In order to assess the differences further, we used a post-hoc Tukey test. This revealed two significant differences, the first between scores on the Hick Task 0-bit and 1-bit center conditions, $t(86) = -3.43$, $p = .003$, and between the 1-bit center and 1-bit spread condition, $t(86) = -2.71$, $p = .02$. Thus, performance on the 1-bit center condition ($M = 359.22$) was significantly slower than performance on the 0-bit condition ($M = 324.0$). Additionally, performance on the 1-bit spread condition ($M = 331.48$) was significantly faster than performance on the 1-bit center condition ($M = 359.22$). There was no difference between performance on the 0-bit ($M = 324.0$) and 1-bit spread ($M = 331.48$) conditions. See Figure 2 for a graphical depiction of these findings.

Table 3

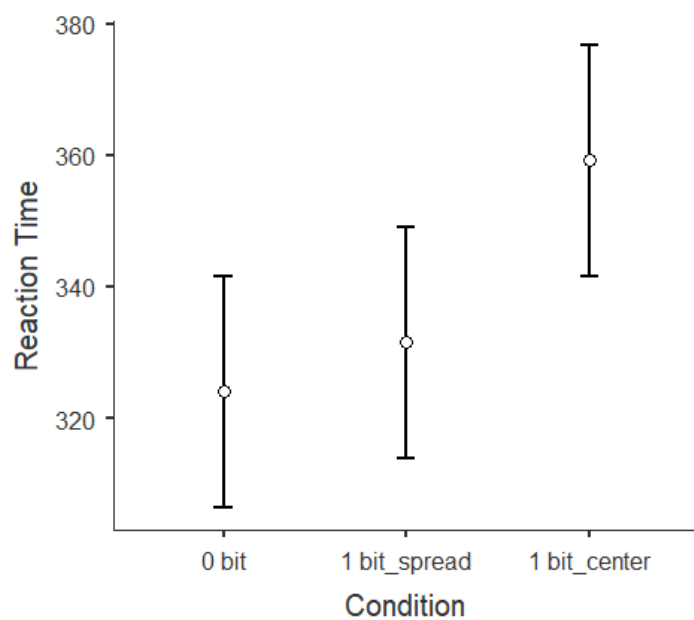
One-way Repeated Measures Analysis of Variance (ANOVA)

	Sum of Squares	df	Mean Square	F	p	η^2
Condition	30238	1.45	20820	6.53	0.006	0.064
Residual	199018	62.45	3187			

Note. Type 3 sums of squares were used with a Greenhouse-Geisser degrees of freedom correction.

Figure 2

Reaction Times as a Function of Hick Task Condition



Note. Bars represent 95% confidence intervals.

Discussion

We had two main hypotheses that we wanted to explore in this study. First, we hypothesized that RTs on the 1-bit spread condition would be higher (and thus slower) than those in the 1-bit center condition of the Hick Task. The second hypothesis was that there would be a significant correlation between performance on the Hick Task, especially for the 1-bit spread condition, and either intelligence (as reported by scores on the RAPM task) or attention control (as reported by scores on the Antisaccade task), if not both. Neither of those hypotheses were supported with the data we collected.

In the comparison between Hick Task 1-bit center and 1-bit spread conditions, we expected that the spread condition would have higher RTs. This was based on the fact that in the spread condition, the attentional breadth confound in the original Hick Task was maintained, while the center condition eliminated that confound (Bors et al., 1993). However, as seen in Figure 2, the spread condition ended up having faster (and thus numerically lower) RTs. Furthermore, we expected that there would be a significant difference between performance on the 0-bit condition (where there is no attentional breadth confound) and the 1-bit spread condition (where the confound is retained), with people having faster RTs on the 0-bit condition. However, there was a significant overlap of confidence intervals between these two conditions (Figure 2). Together, these findings surprised us, as we found a difference in the opposite direction of what we had predicted and found no difference where we had expected there to be one. Furthermore, we expected that there would be a strong correlation between RTs on our modified Hick Task and performance on the RAPM or Antisaccade tasks. However, we did not find results that supported our hypothesis in this regard.

We are cautious to interpret these results substantively due to several anomalous findings. First, we failed to find a relationship between our reaction time measures and RAPM scores, an often prerequisite for testing any theoretical claims concerning the nature and causes of individual differences in intelligence. This relationship, though modest in the literature, has been consistently replicated (Proctor & Schneider, 2018; Sheppard & Vernon, 2008). Likewise, we failed to observe any measurable association between Antisaccade accuracy rates and RAPM scores, which, again, have been a consistent finding (Draheim et al., 2020). Finally, we failed to observe a reliable increase in reaction time between the 0-bit and 1-bit spread condition, which is more consistent with how Hick Tasks have traditionally been done in the 1-bit center condition (Bors et al., 1993). This failure to replicate a classic finding again makes drawing substantive conclusions hazardous.

An important note to mention is the fact that our sample was fairly homogenous, including 44 people who, for the majority, were students enrolled at the Georgia Institute of Technology. Taking a sample from this community cannot be reflective of what correlations may exist in the real world, with more diverse people in age range, ability, and other demographics that were fairly consistent in this study. Additionally, our sample size only included 44 participants, and so having a larger sample size would also allow minimize potential confounding variables that may impact the correlations.

Future Directions

When it comes to future directions with this research study, there are two main approaches that can be taken to further explore the effect (or lack thereof) of attention control on the RT/IQ correlation as reported in the Hick Task. The first category involves procedural improvements, including diversifying and increasing our sample, and adding more attention control and intelligence measures. A larger, more diverse sample would capture the variety in attention, intelligence, and general ability that is found in the true population. By having more attention control and intelligence measures incorporated, we could get a more complete picture of attention control and intelligence, which would help establish the credibility of any correlations that may arise.

Another future direction involves incorporating a structural equation modeling framework to the data collected on a study like this one. Structural equation modeling is useful because it can be used to help establish plausible directionalities. A study of interest used structural equation modeling to isolate experimental variance in a Hick task and establish its relationship with intelligence (Rammsayer et al., 2017). This is a superior approach to other methods that have been used in this area, such as ANOVA testing, because it allows for greater measurement purity and for more elaborate testing of possible explanatory models.

It seems promising to explore attention control as a mediator in the relationship between intelligence and RTs. To this end, future studies can adopt the approach of Rammsayer et al. (2017). By using a non-experimental latent variable to account for variability constant across conditions, and an experimental latent variable to account for variance that changes across experimental conditions, structural equation modeling can show more precisely which facets of Hick RT variability are related to intelligence. Upon doing so, Rammsayer et al. (2017) found

that the experimental variance related to increasing uncertainty was related to intelligence and accounted for 10.9% of the variance in mental ability. Non-experimental variance that was common to all bit conditions did not predict intelligence, however. While many studies look at both SOIP and attention control approaches to understanding intelligence, very few use structural equation modeling in their statistical analyses. Together, the results of Bors et al. (1993) and Rammsayer et al. (2017) suggest a promising avenue to further study the RT/IQ correlation, and move the field towards establishing the directionality of such effects.

Conclusion

For decades, cognitive psychologists have been trying to figure out what is behind the famous RT/IQ correlation. While most researchers in the past have supported the SOIP approach, we believe that attention control plays a role too, as a mediator in the correlation of intelligence and RTs. Our hypothesis was informed by the work of Bors et al. (1993), and we attempted to replicate their work while also expanding it by adding attention control measures.

While we were unable to support our hypotheses, there are several future directions that should be investigated to further explore the role of attention control in the intelligence/RT correlation. These include having a more diverse sample, using multiple measures of attention control and intelligence, and applying a structural equation modeling framework to data analysis.

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